Introduction: Toward the Establishment of a Continental Asian Biostratigraphic and Geochronologic Framework

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Introduction

Strategically located between North America, Europe, and Africa, Asia is at the cross-roads of inter-continental migrations of terrestrial mammals. Asia thus plays a crucial role in our understanding of mammalian evolution, zoogeography, and related questions about first appearances of immigrant mammals in surrounding continents and their roles as major markers of biochronology. As the largest continent, Asia is the locus of origination for many groups of mammals and/or a site of significant subsequent evolution. The temporal and spatial distributions of these mammals in Asia thus provide a vital link to related clades in surrounding continents. Such a strategic role is particularly apparent during the Neogene (~23-2.6 million years ago) when Asia was intermittently connected to Africa and North America, and widely connected to Europe. Asia also occupies the greatest range of climates and habitats, from tropics to arctic and from rainforests to desert zones, often boasting the most fossiliferous regions with fantastic exposures and producing some of the richest fossil mammal localities in the world. It is therefore no exaggeration that Asia is central to a global understanding of mammalian history.

Such importance and opportunity notwithstanding, Asian mammalian biostratigraphy lags behind those of Europe and North America for historical reasons, and many unresolved issues become bottlenecks for a detailed understanding of mammalian evolution elsewhere. Despite a relatively late start, a tremendous surge is seen in recent decades in indigenous researches and international collaborations. Asian mammalian biostratigraphy is at a stage where local or regional frameworks are beginning to take shape, but there is no attempt at linking these regional syntheses to derive a continent-wide perspective. Asian vertebrate paleontologists are largely operating within the borders of their own countries, with infrequent communication across political boundaries. This is in contrast to situations in North America and Europe, where fluid exchange of information and ideas results in continuous refinement of continent-wide chronological schemes that are widely accepted among practitioners (e.g., Woodburne 1987; Steininger et al. 1996; Steininger 1999; Woodburne 2004).

During the last 30 years, an indigenous continental mammalian chronological system has been emerging, mostly based on existing, relatively well-studied faunas in China (Chiu et al. 1979; Li et al. 1984; Qiu 1989; Qiu and Qiu 1990, 1995; Tong et al. 1995; Qiu et al. 1999; Deng 2006). These compilations, however, suffer from some shortcomings. Foremost is constant looking to Europe for reference about relative correlations. To a certain extent, this is inevitable as Asia and Europe constitute essentially a single continent during much of the Neogene and at any given time, the two "continents" share many faunal characteristics. However, this tendency to looking to the west for guidance also breeds a reluctance to build indigenous systems. As a result, discussions about chronology tend to make references to the MN units, as if the latter's "stamp of approval" would somehow make a more reliable age determination. This is unfortunate because many Asian faunas are derived from basins with long and continuous sections, which, with careful magnetic calibrations, can offer superior chronological control than long distance correlations to the MN system ever can.

This book is thus a coming-of-age attempt to synthesize the state of the art. By compiling mammal faunas from all major fossil-producing countries and regions in Asia, we hope to demonstrate that an Asian system can stand on its own, or at the very least be a starting point for further refinements that can ultimately build a major continental system in its own right. This book is the result of a collaborative effort by leading mammalian paleontologists of the world, who gathered in Beijing in 2009 and 2010 for two international conferences for the purpose of formulating an initial framework of Asian continental biostratigraphy (see section below). The complex nature of such a task, which often has to contend with incomplete information, makes it necessarily an interim solution intended to encourage additional research and further debate. A timely publication of this volume, however incomplete it may be in particular areas, stands to gain the most by laying down the principles and practices of mammalian biostratigraphy and geochronology from all regions and countries. Toward this goal, we are confident that a well-established mammalian biostratigraphic framework in Asia will contribute to a global picture of mammalian evolution in a refined chronological context.

Abbreviations: ISG, International Stratigraphic Guide; IVPP, Institute of Vertebrate Paleontology and Paleoanthropology (Beijing); MN, European Neogene Mammal units; NALMA, North American Land Mammal Age.

Background of Beijing Workshops and Genesis of this Volume

The idea of an Asian Neogene biostratigraphic meeting in Beijing with Asia-wide participation came up in late June 2007 while the senior author (XW) was in Beijing. The main impetus was the recognition that there is, thus far, no Asia-wide forum to discuss the feasibility of an Asian land mammal age system. As an emerging power, China seems a natural place to take the initiative, as the country embarks on an unprecedented economic development with attendant renaissance in basic research. China also happens to straddle the mid-latitude desert zones that are often the best hunting grounds for vertebrate fossils in the world. Its long history of "dragon bone" hunting, going back to hundreds of years in traditional medicine, gives it a head start in vertebrate paleontology.

Given above favorable conditions, a meeting proposal, with endorsements from Qiu Zhanxiang, Qiu Zhuding, and Deng Tao, was submitted to the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) in early July 2007. A symposium volume was also included in the proposal. However, organizational efforts did not begin in earnest until April 2008, when IVPP decided that such a meeting would be opportune as a celebration of its 80th anniversary. At this point, co-editors of this volume (LJF and MF) agreed to be involved in the meeting organization and editing of the symposium volume. The main challenge was to raise substantial funds to pay for participants who were otherwise unable to attend. Toward that end, we secured funding from National Science Foundation (NSF, US), National Natural Science Foundation (NSFC, China), Society of Vertebrate Paleontology, as well as institutional support from the IVPP. In particular, we adopted the Critical Transitions workshop (a NSF-NSFC co-funded workshop series on the critical transitions in the history of life) as a unifying theme for international collaborations.

The "Neogene terrestrial mammalian biostratigraphy and chronology in Asia – a workshop and symposium toward the establishment of a continent-wide stratigraphic and chronologic framework" was convened in June 8-10, 2009, at the IVPP, followed by a four-day post-conference field trip to the Linxia Basin in Gansu Province. More than 70 scholars and graduate students participated in the workshop, with representation from 19 countries including Austria, China, Finland, France, Germany, Great Britain, Greece, India, Iran, Japan, Mongolia, Pakistan, Russia, Spain, Sweden, Thailand, Turkey, United Arab Emirates, and United States.

It became apparent during the workshop that existing Chinese mammalian biostratigraphic divisions posses the best potential as the core of an Asian framework, as summarized by Woodburne: “The background of China’s long and fundamental role in developing a chronologic system was clearly recognized in this regard, and the array of approaches to developing chronological systems portrayed at this conference provided the Chinese organizers with considerable examples to draw upon in furthering their goals” (unpublished report to the Society of Vertebrate Paleontology by M. O. Woodburne). As one of the chief architects of the Chinese system developed during the past 20 years, Qiu Zhanxiang was tasked to form a working group for creating such a framework (Qiu Z.-x. et al. this volume). However, it was clear from the beginning, as well as in reviews of various drafts of manuscripts circulated during the workshop, that serious disagreements exist regarding conceptual issues as well as practical problems. Another forum would thus be necessary to give a full airing of the controversies. Toward that end, a second workshop was organized, again funded by the NSF critical transitions theme. This second workshop was held at IVPP, March 8-9, 2010, and attended by a small group of key participants from US, Finland, and China.

This book published by Columbia University Press, following a similar volume on North American mammals (Woodburne 2004), is the culmination of the above efforts. It attempts to bring together the state-of-the-art of Asian biostratigraphy and geochronology with the widest representation possible.

Summary of Workshop Discussions and Resolutions

One of the distinguishing features of the workshops is the open discussion about concepts and practices, as well as the diversity of opinions. Much reflection is given to practices elsewhere in the world. In particular, the European Neogene Mammal units (MN system) and North American Land Mammal Ages are closely scrutinized for strengths and weaknesses in the hope of building a better system. Many of the comments during the workshop are indicative of current sentiments regarding historic developments, and they are briefly summarized below as extractions from meeting minutes with original commentators cited in parentheses when appropriate.

There is general recognition that the European MN system, although very practical and widely used, has some serious limitations, mostly out of necessity rather than by design. By its own nature and often for lack of long stratigraphic sections with unambiguous superpositional relationships, the MN system is a formulation of biozonation that cannot distinguish diachrony even in cases of precise correlation, and the system would not be able to distinguish time differences in correlative faunas (L. Werdelin). Furthermore, correlation errors can be as much as two MN units above and below (M. Fortelius). Whenever possible, therefore, an Asian system should avoid the deficiencies in the MN zonation, which is undergoing revision to improve the basis of those units. For example, current work by Spanish colleagues is recalibrating MN units to base them on a true biostratigraphic framework (J. Agustí).

Given the shortcomings of the MN system, the widely used chronostratigraphic stage ("golden spikes" and associated concepts) in the marine realm seems an attractive approach (M. Böhme). Furthermore, most of the marine Neogene stages have been ratified, and the All-China Stratigraphic Commission has been in full agreement with this approach and has attempted to set Chinese continental Neogene research in motion toward that goal (Qiu Z.-x.). However, there is strong opposition against a chronostratigraphic system by several participants, particularly those who champion an independent system as exemplified by the NALMA. The main problem with golden spikes is that, once nailed, they are no longer flexible, and an Asian system should be based on true biostratigraphy in multiple long sections that can be further refined and revised as new advancements come along (M. Woodburne; see further discussion in Some Conceptual Issues below).

Given the often messy developments of continental land mammal systems, some openly wonder if we should not simply do away with a land mammal age system and use numeric ages instead (F. Bibi). In fact, a biozonation has never been given a high priority in the Siwalik sequence (J. Barry), and people working in South Asia are generally content in talking about absolute ages rather than land mammal ages (L. Flynn). However, most seem to recognize that land mammal ages will always have a place in the formulation of a chronological system because the biological component can never be subjugated under isotopic dating or paleomagnetic dating (M. Woodburne).

Another issue of major concern is the spatial distribution of mammal fossils. Geography is of paramount importance for a super-continent as Eurasia that spans great longitudes and latitudes and crosses many climatic zones. In South Asia and Southeast Asia, roughly the modern Oriental Zoogeographic Province, mammals share much greater similarities during much of the Neogene, whereas the low latitude faunas in southern China and southeastern Asia are generally unlike those from midlatitudes in north China and the rest of central Asia (R. Hanta; L. Flynn). Nonetheless, midlatitude faunas can often be recognized along great longitudinal spans, such as the Pikermi faunas from Greece, which have comparable equivalents in north China (M. Fortelius). It may not be very realistic to devise a biochronological system that crosses the boundary of the Palearctic-Oriental provinces, but it may be possible to develop a system within the Asian part of the Palearctic Province, or at least the eastern part of Asia (see more in Zoogeographic Difficulties below).

The above summary illustrates that an Asian land mammal system faces some challenges common to all continents (fossil mammals are rare; sampling errors are high; diachrony is common) as well as unique challenges in Asia (uneven studies in different countries; lack of marine interface; shortage of datable volcanic rocks interbedded in sediments; high degree of zoogeographic differentiation; some degree of endemism). Recognizing the above challenges, the workshop participants adopted the following resolutions by unanimous consent:

> "*1, an Asian chronologic system, independent from the European MN units, is needed; 2, such a system should be mainly based on biological events, associated with paleomagnetic and isotopic dates where available; 3, existing Chinese system, imperfect as it is, can serve as a starting point that can evolve through time; 4, the benefits of such a system is a common framework in which hypotheses of biological events across the continent can be rigorously tested; 5, a committee headed by Zhanxiang Qiu, Tao Deng, Zhuding Qiu, Chuankuei Li, Zhaoqun Zhang, Banyue Wang, and Xiaoming Wang (additional expertise will be recruited as need arises) will work toward the above goal; and 6, additional subcommittees to clean up taxonomies should be established by relevant specialists.*"

Some Conceptual Issues

Mammalian biostratigraphy has been and still is the primary means for Cenozoic terrestrial geochronology. Continental mammalian biostratigraphic frameworks are integral to related disciplines such as mammalian evolution, zoogeography, paleoecology, and paleoenvironment. Various chronologic frameworks have been established in all continents except Antarctica, but their qualities (precision and internal consistencies) vary greatly, with European and North American systems being the most mature and those of other continents far less so. In developing an Asian land mammal system, much of the focus, both in workshop discussion and in subsequent manuscript development, has thus centered on the best practices in Europe and North America.

Although the Chinese land mammal age system has implicitly or explicitly adopted certain aspects of the European or North American practices, past iterations have mostly been concerned with articulations of the empirical evidence instead of an examination of the methodologies (e.g., Qiu 1989; Qiu and Qiu 1990; Qiu et al. 1999). An introspective assessment of current practices in the world thus represents a welcoming first step to construct a thoughtful system that is both methodologically defensible and practically useful.

From the beginning of the first workshop, it became clear that a European style MN unit system has serious shortcomings because of its general lack of biostratigraphic underpinnings. The MN system, while widely practiced, offers little guidance as a model for Asia. Asia, as in North America, possesses all the potential for developing a framework based on biostratigraphy in long stratigraphic sections. Nonetheless, the MN system is by far the most influential in Asian biochronologic developments due to the wide connections between the two continents and the large number of shared taxa in various ages. So pervasive are the MN units that it is not uncommon for Asian faunas to be directly compared to European ages/MN units or simply to be labeled with a MN unit.

Unity with International Code vs Regional Independence. One of the most controversial subjects during the two Beijing workshops is the desire to follow the International Stratigraphic Guide (ISG) (Hedberg 1976; Salvador 1994). Intense debates center on the suitability of a chronostratigraphic system in continental settings with golden spikes (Global Stratotype Section and Point, or GSSP) nailed on a physical lithostratigraphic section. The debate is set in a background of recent trends in the Chinese stratigraphic community to adopt the ISG protocol, buoyed by the establishment of several Chinese GSSPs for the Mesozoic and Paleozoic eras (e.g., Yin et al. 2001; Chen et al. 2006). The All-China Stratigraphic Commission (2001) went as far as selecting many existing Chinese land mammal units as "stages" and briefly characterized each (within Neogene the following were included: Xiejian, Shanwangian, Tunggurian, Baodean, Gaozhuangian, and Mazegouan). To push these efforts further, the commission distributed grants to the IVPP to flesh out Cenozoic stages in China, which resulted in some preliminary boundary selections, mostly coinciding with those endorsed by the ISG (e.g., Deng et al. 2003; Deng et al. 2004; Deng et al. 2006; Meng et al. 2006; Deng et al. 2007).

Whereas the GSSP standard promoted by the ISG is largely accepted in the marine stratigraphic community, it is far from certain how a continental system should proceed given its inherent problems in depositional gaps, rareness of fossils, patchiness in distribution, and insularity of paleoenvironments. While there is general agreement that such factors call for regionally limited chronological systems, commonly at the continental scale or smaller, opinions are deeply divided regarding how to construct such a system and whether such a system should be consistent with the ISG recommendations. A prominent example is the North American Land Mammal Age system, which enjoys wide acceptance among North American vertebrate paleontologists but is at variance from the recommendations of the ISG. Fundamental to the premise of the NALMA is the recognition that there is no inherent reason why events in land mammal evolution should coincide with those of marine organisms from half a world away. In fact, part of the initial impetus by the "Wood Committee" to establish the North American "provincial ages" is an attempt to avoid the "dangerous ambiguity, cumbersome circumlocution, or both" when trying to correlate to the European standard time scale (Wood et al. 1941: 2).

Following the recommendations by the All-China Stratigraphic Commission (2001), Qiu et al. (this volume) propose a Chinese Regional Land Mammal Stage/Age system that they envision will ultimately transition to one fully consistent with the ISG standards. Chronostratigraphic boundaries of such a system are based on multiple criteria of lithostratigraphy, magnetostratigraphic reversals, and mammalian first appearances and faunal characterizations. In doing so, Qiu at al. point out that the NALMA also uses lithologic criteria, at least in the case of the lower boundary of the Arikareean. They further argue that land mammal ages cannot be equated to biochrons. In fact, in their opinion, biochrons have no place in a regional chronostratigraphic system. As a step further in making all land mammal stage/age systems conformable to the international standard, Qiu et al. propose that for those mammal ages whose lower boundaries are near the standard international boundaries of a higher rank, such as the Oligo-Miocene and Mio-Pliocene boundaries, the mammal age boundaries should coincide with the epoch boundaries.

Bringing their vast experience in the North American land mammal age system to bear, Woodburne et al. (this volume), on the other hand, proposed a framework of an endemic North China mammalian biochronologic system as an evolving standard of temporal intervals that accounts for all of Neogene time without gaps or overlaps. They suggest that such a system represents informal biochronologic units, and until this system has been widely tested, formalized international chronostratigraphic standards should not be applied. Woodburne et al.'s premise is that a land mammal age system should always give fossil mammals prominent consideration. Methodologically they strongly advocate for a single taxon definition of mammal age boundaries in order to minimize potential gaps and overlaps.

In a compromise approach, Meng et al. (this volume) used the Xiejian as an example to illustrate their single-criterion, single-taxon definition but largely within the chronostratigraphic framework recommended by the ISG. As such, Meng et al.'s scheme allows future adjustments of boundary definition but it must be tied to a specific stratotype section. Their Xiejian example also explores the case where a stage/age in question roughly coincides with a major international boundary of higher rank (in this case Oligo-Miocene boundary). They treat these two boundaries as strictly separate entities and place the Xiejian lower boundary 0.5 myr above the international Oligo-Miocene boundary.

The above controversy pits chronostratigraphic boundary definition as a convention serving to standardize nomenclature against a more dynamic land mammal age scheme (as practiced by North American paleontologists), emphasizing empirical evidence and flexibility of shifting boundaries. To a certain extent, the former seems to signal a desire to move toward an internationally accepted, marine invertebrate norm, whereas the latter represents a more self-confident approach to a regional, continental mammal-based system divorced from ISG standards.

Zoogeographic Complexity

As the largest continent on Earth, Asia defies easy categorization. With vast latitudinal, longitudinal, and altitudinal spans, as well as the attendant climatic zonations, zoogeographic differentiations are profound (Fig. 1). Indeed, in Alfred Russel Wallace's (1876: map 1) classic map of zoogeographic provinces, the boundary between Palearctic and Oriental provinces was drawn within Asia, mostly along the southern slopes of the Himalaya Range and its lateral extensions. In other words, northern Asia and Europe are zoogeographically more similar to each other than either is to southern Asia. This pattern of modern zoogeographic division can be traced back in deep time at least to the early Neogene, if not earlier, based on fossil mammals (Qiu and Li 2003, 2005; Flynn 2008). Climatic differentiations are similarly recorded by Neogene mammal records (Fortelius et al. 2002; Fortelius et al. 2003; Fortelius et al. 2006; Liu et al. 2009). Given such complexity in geography and climate, questions naturally arose during the workshops as to the feasibility of devising an Asia-wide land mammal age system that can work across major zoogeographic boundaries. If Europe and East Asia within the Palearctic Province are to have a separate chronologic system, shouldn't South Asia in the Oriental Province have its own?

The East-West Divide between Europe and Asia. The Eurasian continent spans the entire eastern hemisphere and beyond. Since the disappearance of the epicontinental Turgai Sea by about early Oligocene, Europe and Asia have been a single connected landmass. Despite this continuity during the Neogene, however, distant faunas from the extreme ends in western Europe and eastern Asia show marked early Miocene differences, although there is a tendency for increased similarity through time (Ataabadi et al. this volume). A climatic gradient is likely, since shear distance probably cannot fully account for such faunal differences.

Diamond (1997) advanced the thesis that organismic (including human) migrations are easily achieved along the east-west (longitudinal) axis because Earth's atmospheric variances are often organized latitudinally, i.e., organisms can readily adapt to habitats of similar climatic zones of similar latitudes. This is in contrast to the north-south axis, which entails the crossing of climatic zones. By this argument, western Europe and eastern China, both of similar latitudes, should share more faunal similarities despite their vast geographic distance. Existence of distinct faunas from Europe and eastern Asia thus indicates climatic differentiations (wetter Europe vs. drier central and eastern Asia), or distinct environmental barriers, such as deserts in central Asia and the Tibetan Plateau. Faunal distinction through much of Neogene (few species in common) is the strongest rationale for an Asian land mammal age system independent of the European MN units. This is in contrast to North America, which has a much narrower longitudinal span and its paleofaunas have even narrower distributions within the western half of North America (eastern North America is poorly fossiliferous). As a result, faunal differences between Pacific coastal states and the Great Plains are small enough to be subsumed within a single NALMA system.

Despite these east-west faunal differentiations, however, broad faunal similarities can be recognized in much of western and central Asia at select time periods. For example, the notion of a Pikermian paleobiome recognizes a wide swath of Eurasia during the late Miocene that is dominated by dry climate, increasingly open environments, and seasonally adapted mammals (Bernor et al. 1996). Such a widespread biome of long duration has been termed the Pikermian chronofauna (Eronen et al. 2009), which lends support for Asian land mammal ages spanning at least northern Asia. As demonstrated by Ataabadi et al. (this volume), such a concept may also be applicable in parts of Eurasia in the middle Miocene, as represented by the Tunggurian chronofauna, although the evolving nature of this chronofauna from an earlier appearance in western Europe and migrating east to eastern China near the latest middle Miocene implies diachrony. Such diachrony has obvious implications for correlation, a case in point being the carnivore genus *Dinocrocuta*, which in Europe and western Asia is a good indicator of early late Miocene age and has been used to support a Vallesian correlation of Bahean age localities in China. Recent studies suggest, however, that *Dinocrocuta* has a primarily (or even exclusively?) Turolian age range in China, with the best dated records so far clustering around 8 Ma (Zhang et al., this volume).

The North-South Divide between North and South Asia. A first-order zoogeographic division between the Palearctic Province to the north and Oriental Province to the south was long recognized to be the result of Earth's surface processes (Wallace 1876). Such a clear distinction is rooted in the following two inter-related processes: erection of a formidable geographic barrier in Tibet-Himalaya and its lateral extensions, and formation of summer monsoons in South and East Asia and winter westerlies and northwesterlies in northern China and central Asia. This factor, coupled with major West-East river systems, distinguishes much of China. A Palearctic/Oriental style provinciality can be recognized since the early to middle Miocene based on small mammal records in eastern China (Qiu and Li 2003, 2005), large mammals from the northern rim of the Tibetan Plateau (Qiu et al. 2001), and small mammals from South Asia (Flynn 2008). Furthermore, in contrast to a progressively more faunal homogeneity between east and west Eurasia during the Neogene (see above), the north-south faunal division is progressively more clearly delineated through time as Tibet was being uplifted and its climatic effects became more pronounced. The above process thus presents the biggest obstacle in the establishment of a truly Asia-wide land mammal age system.

Intermittent Connections between Africa and South Asia. Faunal exchanges between Africa and South Asia, either by direct migration through the Arabian Peninsula or by indirect routes of western Europe (across the Strait of Gibraltar), are evidenced by records from the Siwaliks and equivalent deposits of Dera Bugti and Sulaiman areas (Antoine et al. this volume) (Barry et al. 1991; Flynn et al. 1995). Being in similar latitudes and warm climates, the main control of Africa-South Asia dispersal was by intermittent land corridors. It is thus not surprising that South Asia often has the largest number of African elements outside of Africa, and an Ethiopian-Oriental connection seems to be recognizable (Flynn and Wessels this volume), featuring occasional dispersals in both directions, notably among rodents and primates.

Connection of North America and Asia. Since the early Miocene, immigrants to North America from Asia seem to suggest a closed Bering Strait for much of the time (Woodburne and Swisher 1995). The Bering Land Bridge undoubtedly acts as a filter that allows faunas in the Arctic realm to pass freely, but severely limits those from middle or lower latitudes. Because of this limited faunal exchange, correlations of Asian and North American land mammal ages, which are entirely based on mid-latitude faunas, are not easy and the NALMA did not have much influence on the developments of the Asian mammal system.

Contributions of Asia-North America faunal exchange are often asymmetrical; a large number of immigrant events have been recorded in North America, but far fewer mammals made it to Asia. Tedford et al. (2004: fig. 6.3) counted 88 allochthonous genera of Old World origin during the Arikareean through Hemphillian; many of these have become a significant part of local community in North America. With the exception of horses (*Anchitherium*, *Hipparion*, *Equus*), camels (*Paracamelus*), and dogs (*Eucyon*, *Nyctereutes*, *Vulpes*), mammals that dispersed from North America have not exerted a corresponding presence in Asia. Although such a discrepancy can potentially be accounted for by sampling effects, at least in the Pliocene (Flynn et al. 1991), it is also possible that a larger Eurasian continent presented a more competitive environment for North American newcomers. One striking example is an early Pliocene Arctic North American fauna that shares close similarity with contemporaneous faunas from north China (Tedford and Harington 2003).

Critical Transitions

This book is the result of collaborative efforts in two Beijing workshops, which is part of a Sino-US collaborative research agenda on critical transitions in the history of life. The goal is to address critical transitions in geologic history that profoundly affect biological and environmental evolution on global scales. Once again, Asia, by its unique geographic position and geologic history, has much to offer in our understanding of global environmental changes. Mammal distributions in space (zoogeography) and time (biostratigraphy and geochronology) are two key components in any attempt to formulate ideas about paleoenvironmental change. In many ways, mammal biostratigraphy by itself offers evidences of critical transitions. In that sense, we hope this volume will provide the initial dataset and encouragement to stimulate further research on the various critical transitions.

Looming large in any Asian Cenozoic geologic events is the rise of the Himalayan and Tibetan highlands and effects on the initiation of Indian and East Asian monsoon climates. Without doubt, Himalaya-Tibet, as an imposing physical entity in central Asia, is a first-order climate maker. Much debate, however, is centered on the timing and process of the coupling of mountain uplift and climate change, and their feedback on erosion and weathering (e.g., Molnar

2005). From a paleontological perspective, mammals as a biological component and a chronological marker have much to offer in this debate.

The emergence of Himalaya-Tibet and the ensuing zoogeographic division of Palearctic and Oriental provinces affects mammal distributions in two ways. The rising Himalaya coupled with drastic changes in climatic zonation form an effective barrier for all but high-flying birds. Once again, fossil mammals offer direct evidence for this profound change. Furthermore, as consumers of vegetation, mammalian ungulates are also invaluable for assessing plant compositions. Isotope ratios of dental enamels, hypsodonty indices, microwear and mesowear have become critical means to deduce plant coverage, paleotemperature, and precipitation. As the field matures, such "ecometrics" (Eronen et al. 2010) are likely to become welded into an increasingly quantitative paleoenvironmental framework that can be used in conjunction with of paleoclimate modeling to constrain and refine reconstructions of past conditions and processes (Eronen et al. 2009).

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Caption for Figures

Figure 1. Schematics of inter- and intracontinental faunal interchanges and dispersals centered around Asia. Europe-East Asia faunal interchange is largely in the same latitudes in the east-west direction; the main barrier is the arid regions in Central Asia and Tibetan Plateau. Except mammals adapted to the Arctic regions, the Asia-North America dispersal has a large component of "vertical axis" (along longitude) and mammals must cross different climate zones in order to reach to the other side. Thin airs and high mountains present a formidable barrier along the southern slopes of Himalaya, which forms a sharp zoogeographic boundary; to the east along east coast of China, however, the boundary becomes fuzzy and a transitional zone shifts along with climate changes. Africa-Asia connection is intermittent during the Neogene. Grey tones in continents roughly reflect the amount of vegetation: white or light grey indicate desert or dry environments and darker grey indicates more vegetation coverage. Width of arrows is suggestive of magnitude of terrestrial dispersals.